A New Approach to Design MIMO Antennas using FSS with Improved Performance

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Forum for Electromagnetic Research Methods and Application Technologies

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Abstract

A new technique to design MIMO antennas with superior performance in terms of correlation coefficient is discussed in this presentation. Unlike the conventional approach where port isolation is increased to reduce correlation coefficient, the proposed approach adopts decorrelation of the radiation patterns of individual elements. To achieve this, a phase-gradient partially reflective surface (PRS) is used as a superstrate above the antenna elements in a low profile Fabry-Perot (FP) cavity configuration. The effectiveness of the method is demonstrated by designing the system for a two-element MIMO antenna at 5.25 GHz and a four-element MIMO antenna at 10 GHz. The proposed technique results in more than 95% reduction in the correlation coefficient value, thus projecting better MIMO performance. The proposed technique can be easily used to design radome enclosed MIMO antennas.

Keywords: *Multiple-input-multiple-output (MIMO), Correlation Coefficient, Fabry-Perot Cavity Antenna, Partially Reflective Surface (PRS)*

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Biography

Dr. Khan is an Assistant Professor at the Research Institute for Microwave and Millimeter Wave Studies (RIMMS), National University of Sciences and Technology (NUST), Pakistan. He obtained his Bachelors in Electrical Engineering degree from Pakistan Navy Engineering College (PNEC), National University of Sciences and Technology (NUST), Karachi, Pakistan in 2006. He received his M.S. degree in Electrical Engineering from GIK Institute of Engineering Sciences and Technology (GIKI), Topi, Pakistan in 2008. He received Ph.D. in Electrical Engineering from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia in 2015. His research focus during his doctorate studies was on Microwave and Antenna Systems Design. As part of the Antennas and Microwave Structure Design (AMSD) laboratory at KFUPM, he worked on Electrically Small Antennas and MIMO Antenna Systems.

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Presentation Flow

- Introduction to MIMO Systems
- MIMO Antennas
- The Correlation Coefficient
- Existing Methods to Reduce Correlation Coefficient
- New Approach
- Design Examples
- Conclusions

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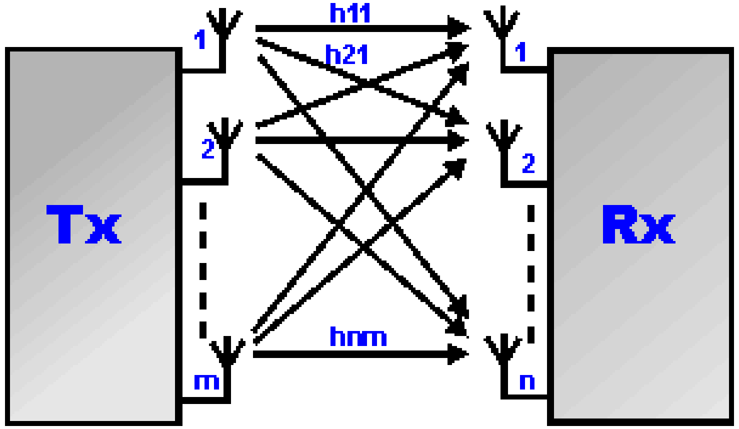
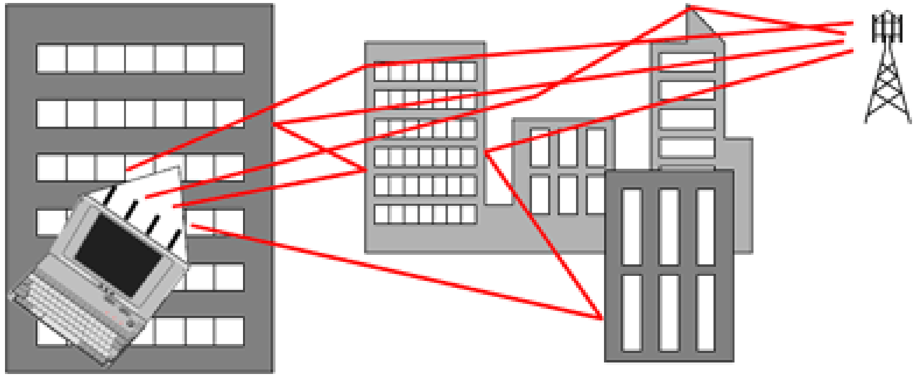
Introduction

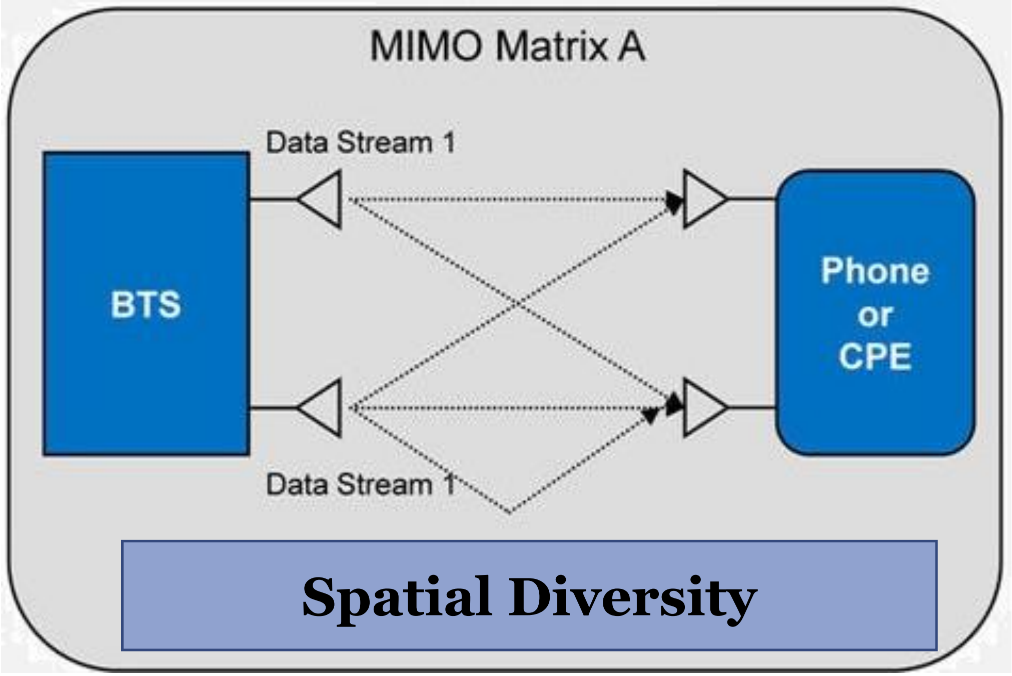
- Systems containing multiple transmit antennas and multiple receive antennas



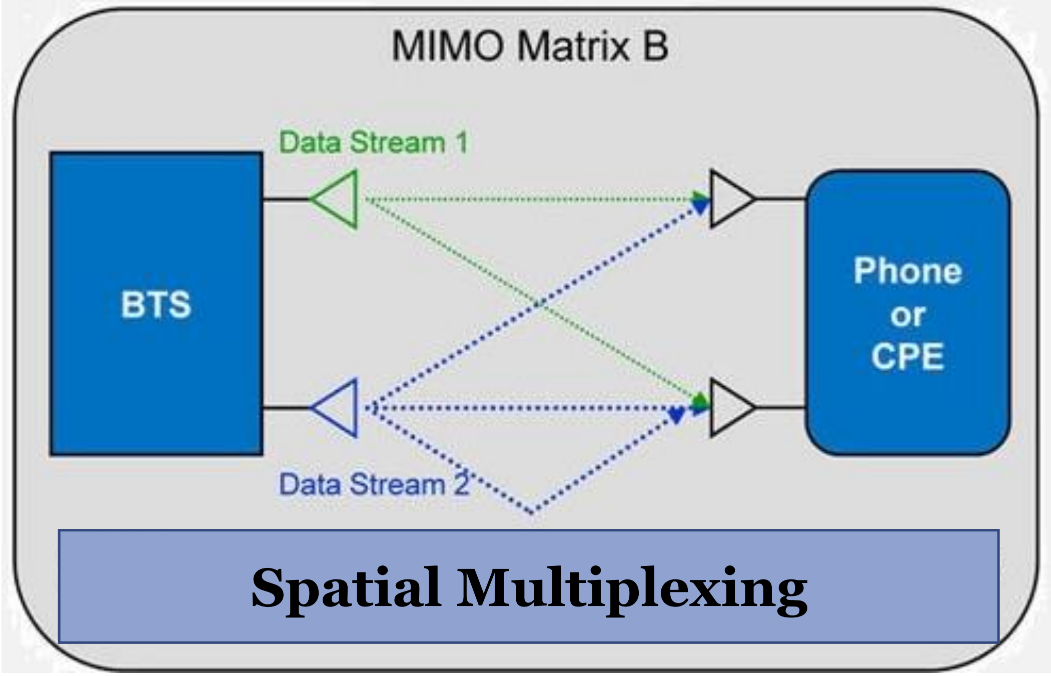
- Enhance communication performance either by;
  - Combatting multipath, or
  - Exploiting multipath



Categories of MIMO Systems


MIMO Matrix A
Data Stream 1
BTS
Phone or CPE
Data Stream 1

Spatial Diversity


MIMO Matrix B
Data Stream 1
BTS
Phone or CPE
Data Stream 2

Spatial Multiplexing

Transmit and receive duplicate copies of a single information stream to increase the reliability of detection

Performance Metric: *Diversity Gain*

Sending distinct information streams over the channels to increase data rate or spectral efficiency

Performance Metric: *Multiplexing Gain*

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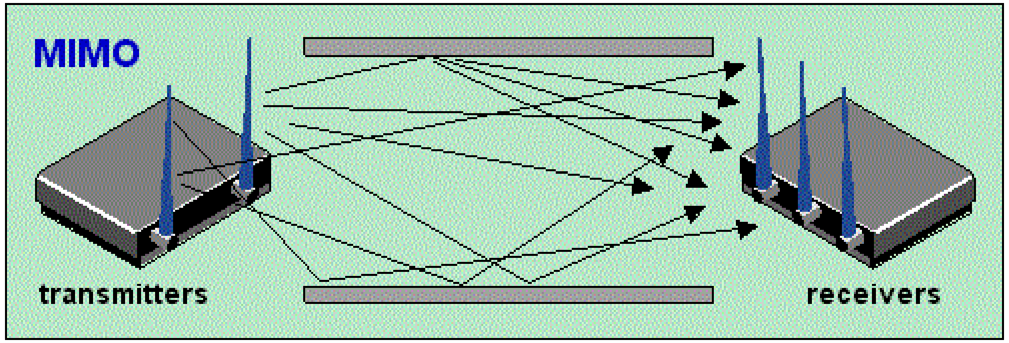
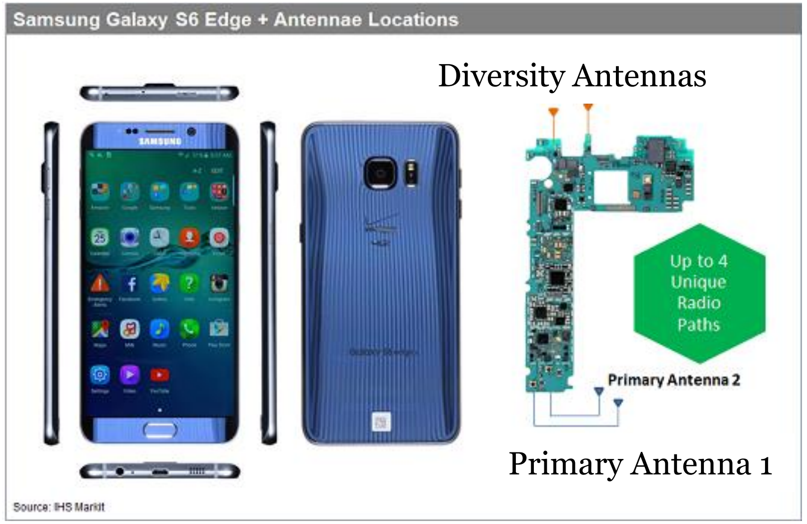
Applications of MIMO Systems

- Any rich multipath communication scenario
- IEEE 802.11n: For data rates of upto 600 Mbps
- Pivotal in achieving the required reliability and data rate in current 4G standards
- Will play a major role in the upcoming 5G standards


MIMO
transmitters
receivers


Samsung Galaxy S6 Edge + Antennae Locations
Diversity Antennas
Up to 4 Unique Radio Paths
Primary Antenna 2
Primary Antenna 1
Source: IHS Markit

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Significance

- Coding and signal processing are key elements of a MIMO system

but

- It is the propagation environment and antenna parameters that affect system performance significantly

*Pan, Yan, Yuehui Cui, and RongLin Li. "Investigation of a triple-band multibeam MIMO antenna for wireless access points." *IEEE Transactions on Antennas and Propagation* 64, no. 4 (2016): 1234-1241.

MIMO Antennas

Performance Parameters

- **Total Active Reflection Coefficient (TARC)**
  - A single parameter to determine the resonance frequency and impedance bandwidth of MIMO Antennas
- **Mean Effective Gain (MEG)**
  - Represents the effect of the environment on the antenna’s radiation characteristics
- **Branch Power Ratio**
  - Ratios between the power levels of various branches
- **Correlation Coefficient**

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The Correlation Coefficient

Introduction

- Describes how much the communication channels are independent or correlated with each other.

- Considers the radiation patterns of the individual elements,

- Computes the degree of correlation they will add among the channels in a particular propagation environnent.

The Correlation Coefficient

Computation

- Normally, an isotropic propagation environment of balanced polarizations is considered.
- Under such conditions, the correlation coefficient (ρ) is defined as;

$$\rho = \frac{\left|\int\int_{4\pi}[\overrightarrow{F_1}(\theta,\phi) * \overrightarrow{F_2}(\theta,\phi)]\,d\Omega\right|}{\sqrt{\int\int_{4\pi}|\overrightarrow{F_1}(\theta,\phi)|^2 d\Omega \int\int_{4\pi}|\overrightarrow{F_2}(\theta,\phi)|^2 d\Omega}}$$

  - F_i (θ ,ϕ) is the complex field pattern of the antenna when the i^{th} port is excited
  - * represents the Hermitian product
  - Denominator represents normalization

The Correlation Coefficient

Computation (contd.)

- The computation of far-fields (both magnitude and phase) in 3D is difficult and time consuming
- For ease of computation, an expression based on S-parameters was developed*;

$$\rho = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|}{[(1-(|S_{11}|^2+|S_{21}|^2))(1-(|S_{22}|^2+|S_{12}|^2))]^{\frac{1}{2}}}$$

- Claimed to be valid for lossless antennas

*S. Blanch, J. Romeu, and I. Corbella, “Exact representation of antenna system diversity performance from input parameter description,” Electronics letters, vol. 39, no. 9, pp. 705–707, 2003.

Goal

- Goal: Low correlation coefficient
- Why: The lower the correlation between channels, the higher is the Diversity / Multiplexing Gain
- Challenge: To achieve a low correlation coefficient in a low form factor

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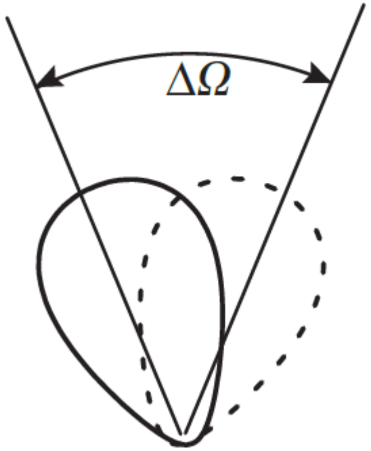
Existing Methods to Reduce Correlation Coefficient

Method 1

- Element Design, Placement and Orientation

$$\rho = \frac{\left|\int_\Omega \left[E_{1\theta}E_{2\theta}^* + E_{1\phi}E_{2\phi}^*\right] d\Omega\right|}{\sqrt{\int_\Omega \left[E_{1\theta}E_{1\theta}^* + E_{1\phi}E_{1\phi}^*\right] d\Omega \int_\Omega \left[E_{2\theta}E_{2\theta}^* + E_{2\phi}E_{2\phi}^*\right] d\Omega}}$$

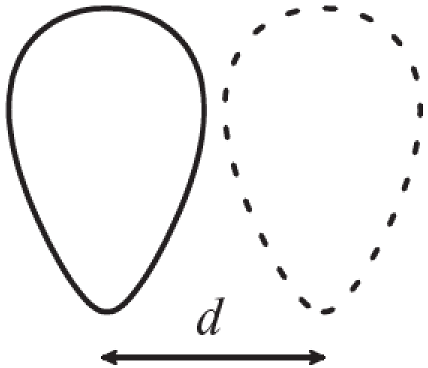
Elements with tilted beam



*

Electrically large structures / arrays required

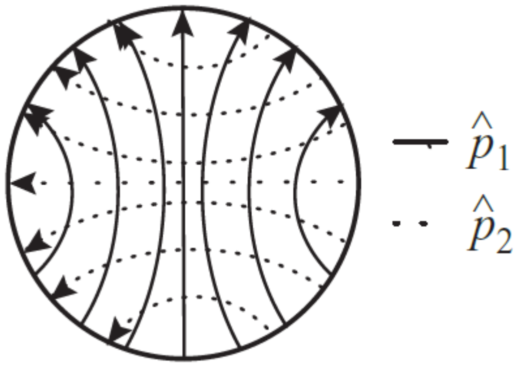
Elements placed far apart



*

Large space required

Orthogonally polarized elements



*

Valid for two elements only

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* Vaughan, Rodney, Jørgen Bach Andersen, and J. Bach Andersen. *Channels, propagation and antennas for mobile communications*. Vol. 50. IET, 2003.

Existing Methods to reduce Correlation Coefficient

Method 2

- Overall Antenna Structure
  - Employs methods to enhance “port isolation” between multiple elements;

$$\rho = \frac{|S_{11}^{*}S_{12} + S_{21}^{*}S_{22}|}{[(1-(|S_{11}|^2+|S_{21}|^2))(1-(|S_{22}|^2+|S_{12}|^2))]^{\frac{1}{2}}}$$

  - Methods used:
    - Decoupling networks
    - Neutralization lines
    - Negative group delay lines
    - Parasitic elements
    - FSS / Metamaterial walls
    - Modified / Defected Ground planes
    - Combination of these methods

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Existing Methods to reduce Correlation Coefficient

Method 2 (contd)

- Drawbacks
  - Some of these works rely on the S-parameter expression for the calculation of ρ;
    - ➢ References* show that this calculation method, in most of the cases, leads to inaccurate results;
      - ❖ Antennas are not lossless (practical case)
      - ❖ Weak / negligible coupling between elements
      - ❖ Object / another antenna element in surrounding
  - Possible that the reduction in ρ occurred because the isolation enhancement structure coincidentally ended up in tilting the radiation patterns of the antenna elements

*S. M. Mikki and Y. M. Antar, "On cross correlation in antenna arrays with applications to spatial diversity and mimo systems" IEEE TAP, 2015

*M. S. Sharawi, A. T. Hassan, and M. U. Khan, "Correlation coefficient calculations for mimo antenna systems: a comparative study" IJMWT, 2017

Existing Methods to reduce Correlation Coefficient

Method 2 (contd)

- Conclusion
  - High Port Isolation does not guarantee a low correlation coefficient

Why?

  - The far-fields of the antenna elements are not targeted directly

New Approach

Core Idea

- A technique wherein ρ is reduced by decorrelating the radiation patterns of individual MIMO elements

$$\rho = \frac{\left| \int \int_{4\pi} [\overrightarrow{F_1}(\theta,\phi) * \overrightarrow{F_2}(\theta,\phi)] d\Omega \right|}{\sqrt{\int \int_{4\pi} |\overrightarrow{F_1}(\theta,\phi)|^2 d\Omega \int \int_{4\pi} |\overrightarrow{F_2}(\theta,\phi)|^2 d\Omega}}$$

- Tilting the beams of elements in opposite directions

- Other MIMO antenna parameters e.g. branch power ratio not affected

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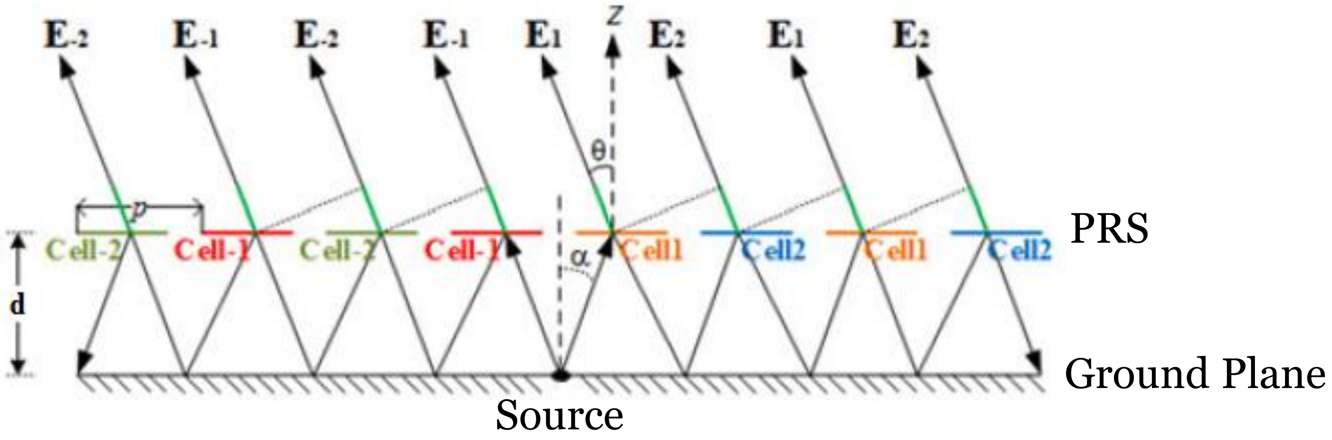
New Approach

Methodology

- If beams not directive, only tilting them will not be enough
- Possible Option: Constructing a Fabry-Perot cavity


E_{-2}
E_{-1}
E_{-2}
E_{-1}
E_1
z
E_2
E_1
E_2
θ
p
PRS
Cell-2
Cell-1
Cell-2
Cell-1
α
Cell1
Cell2
Cell1
Cell2
d
Ground Plane
Source

- PRS (Partially Reflective Surface): an FSS superstrate, large |r|
- Coherent combination of reflected waves → directive beam

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New Approach

Methodology (contd.)

- Cavity Height

$$d = (\phi_{PRS} + \phi_G)\frac{\lambda}{4\pi} + 2N\pi$$

Reflection Phase of PRS

Reflection Phase of Ground

- Conventional Height: $\lambda/2$ ($\phi_{PRS} = \pi$)
- Reduced Height: $\lambda/4$ ($\phi_{PRS} = 0$): using an artificial magnetic conductor (AMC) as the PRS
- Realized using both sides of a PCB; One layer capacitive, one layer inductive
- Acceptable reflection phase for AMC: -90° to 90°

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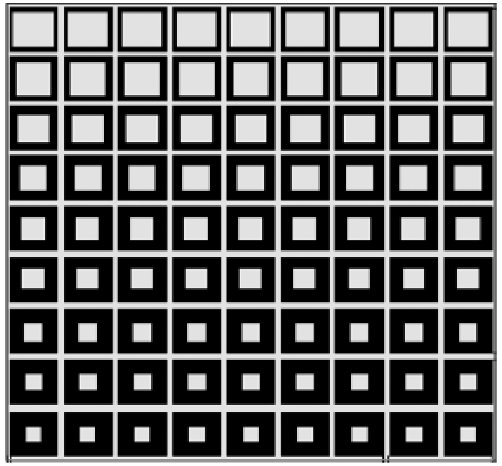
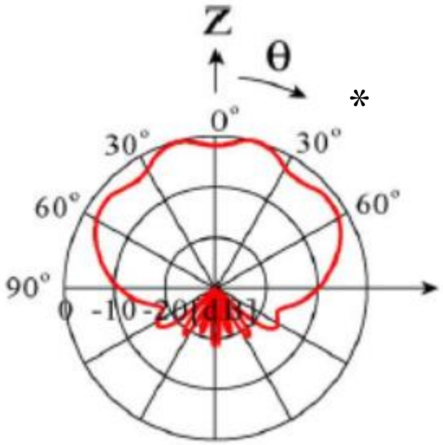
New Approach

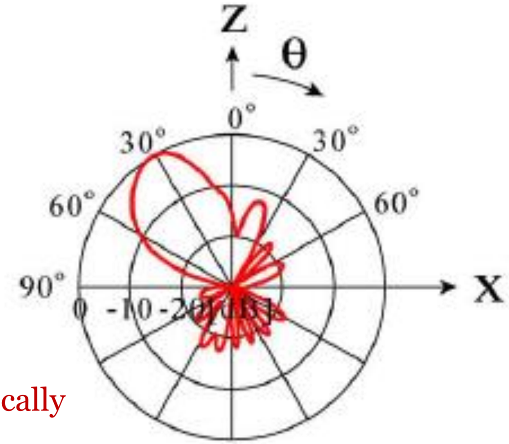
Methodology (contd.)

- Beam Tilting
  - All unit cells identical → Beam in boresight direction
  - Unit cells with dimensional / phase gradient → Tilted Beam
  - Adopt for MIMO elements to tilt beam in opposite directions



Phase Gradient PRS





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* H. Nakano, S. Mitsui, and J. Yamauchi, "Tilted-beam high gain antenna system composed of a patch antenna and periodically arrayed loops," IEEE Transactions on Antennas and Propagation, vol. 62, no. 6, pp. 2917–2925, 2014.

Design Examples

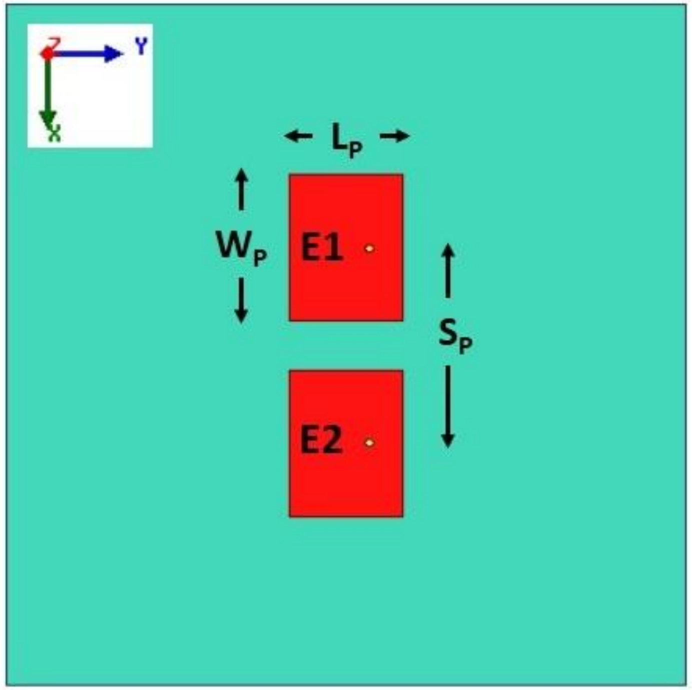
Introduction

- Two different set of MIMO antennas are designed using the proposed approach
- The technique is successfully demonstrated on
  - 2-Element MIMO Antenna
  - 4-Element MIMO Antenna

Design Examples

2-Element MIMO Antenna

- Rectangular Patch Elements designed for 5.2 GHz WLAN Band
- Substrate: RT/Duroid 5880 (ε_r=2.2, h=1.57mm)
- L_p = 17.5mm, W_p=22.57mm, S_p = 30mm
- Edge to Edge Separation: 7.43mm (0.13 λ)



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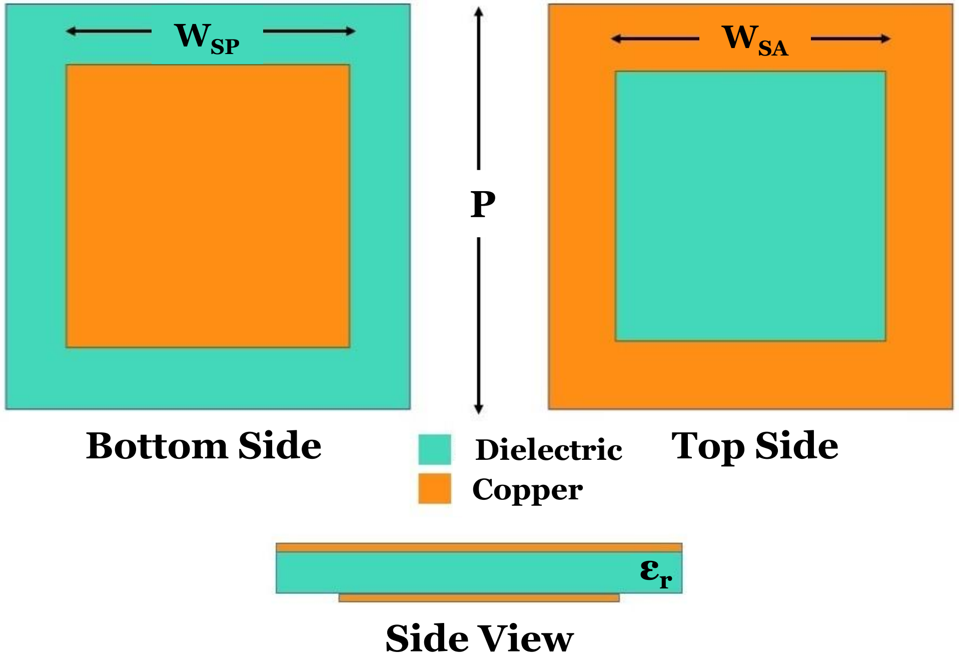
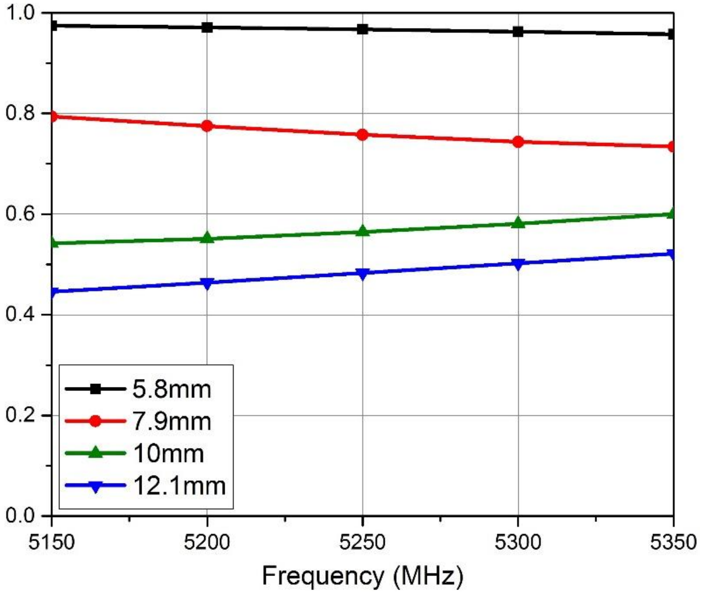
Design Examples : 2-Element MIMO Antenna

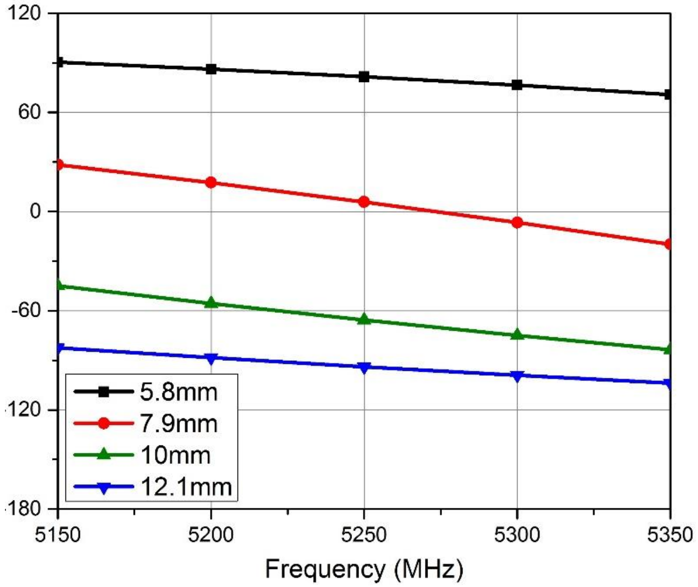
PRS Unit Cell



W_{SP}
P
W_{SA}
Bottom Side
🟩 Dielectric
🟧 Copper
Top Side
ε_r
Side View



Reflection Magnitude



Reflection Phase

- Substrate: Rogers RO4003C (ε_r=3.55, h=1.52mm)
- W_{SP} = 10.5mm, P = 15mm ($\lambda_g/2$), W_{SA} is varied
- Simulation as a periodic structure carried out in HFSS

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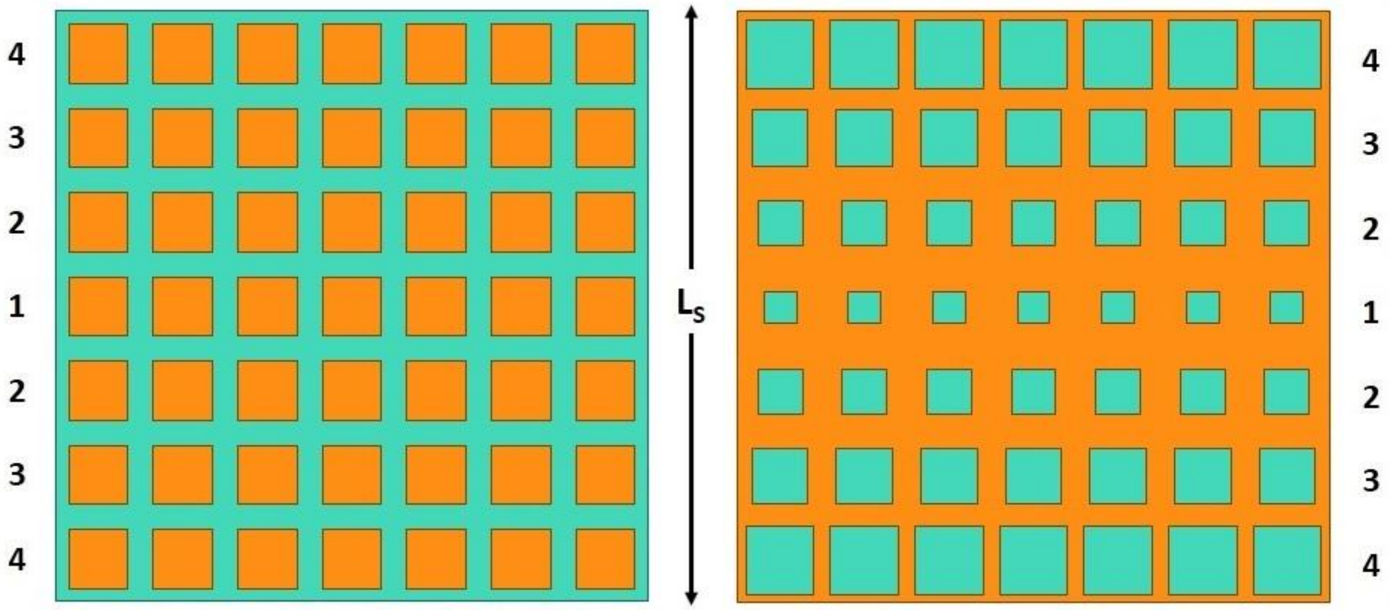
Design Examples : 2-Element MIMO Antenna

PRS Design

Values at 5.25 GHz

ID	W_{SA} (mm)	Magnitude	Phase (deg)
1	5.8	0.97	81.64
2	7.9	0.76	5.84
3	10	0.56	-65.57
4	12.1	0.48	-93.92

- 7 x 7 unit cells
- L_s = 105 mm (1.84 λ)



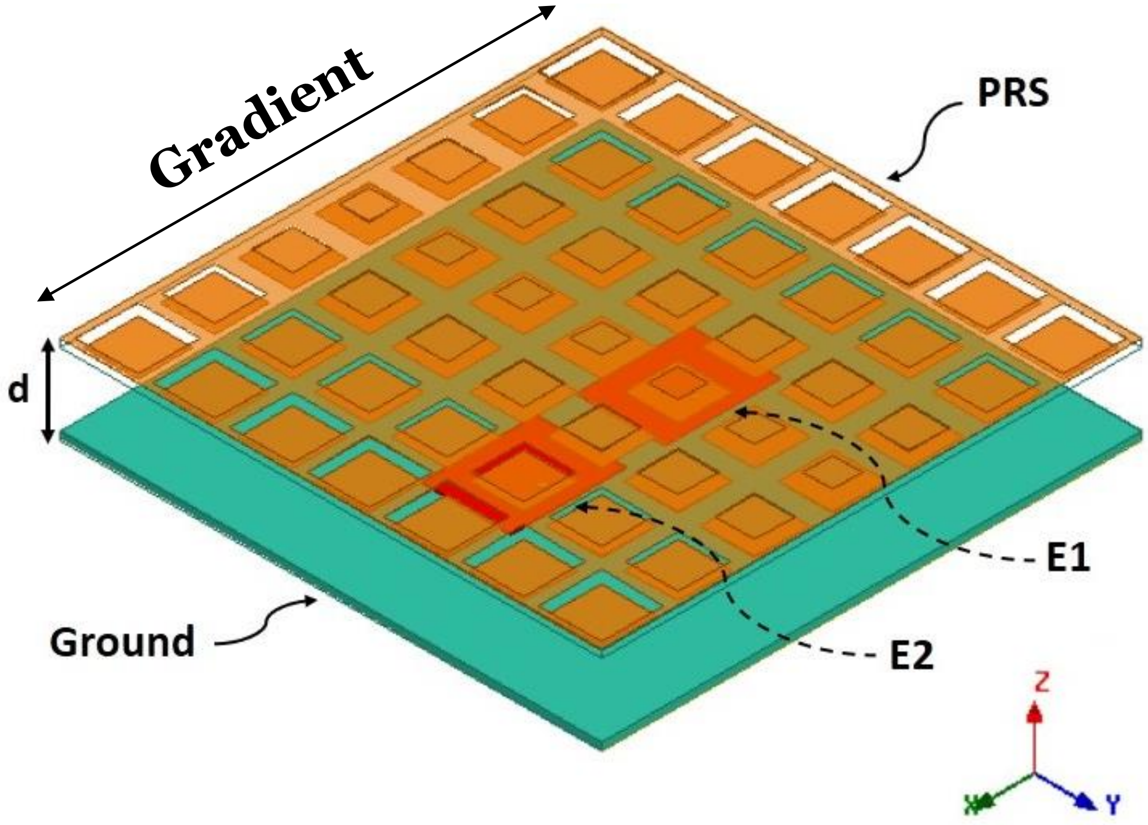
Capacitive Bottom Layer
(capacitance between adjacent patches)

Inductive Top Layer
(inductance of mesh grids)

🟩 Dielectric
🟧 Copper

Assembled System

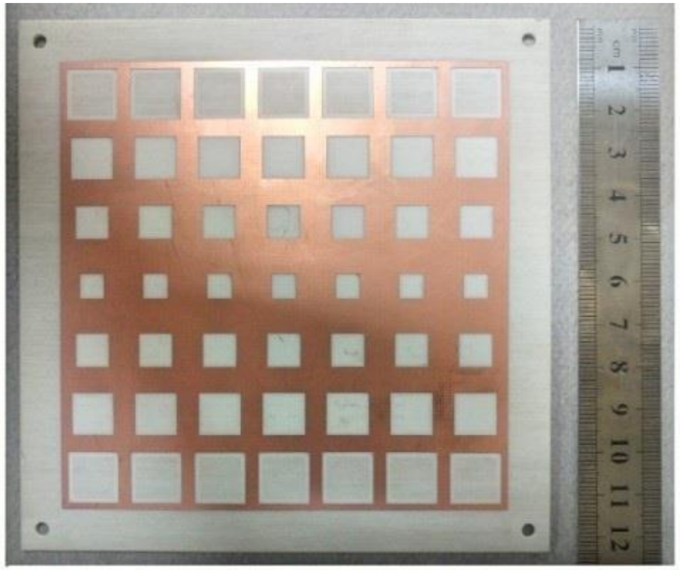
- d = 14 mm (~λ/4)
- A symmetric system
- Orientation of PRS: Gradient along the line on which the two elements lie

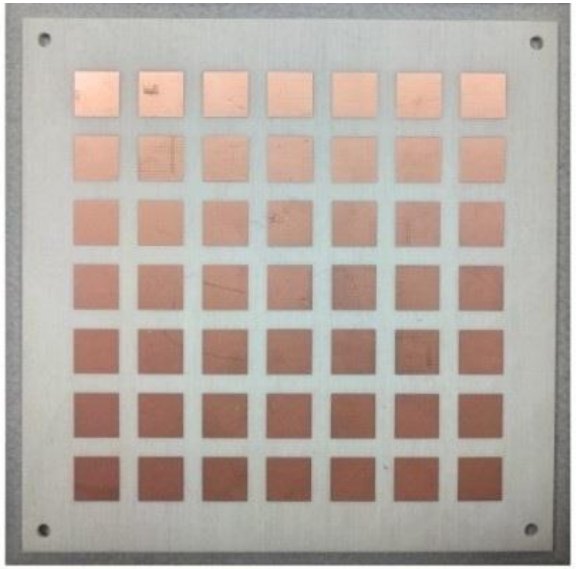

Gradient
PRS
d
E1
E2
Ground
Z
X
Y

Design Examples : 2-Element MIMO Antenna

Fabricated Prototype

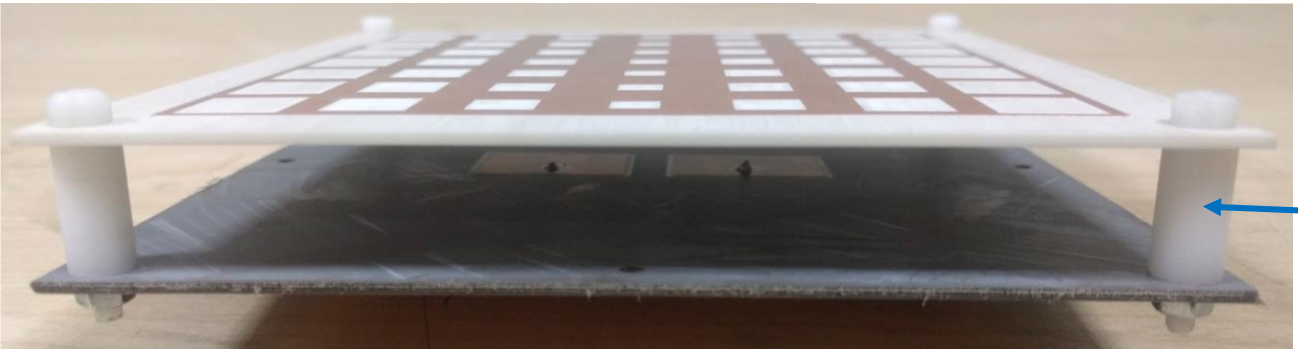
Top Side





Bottom Side

Assembled System



Plastic Spacer

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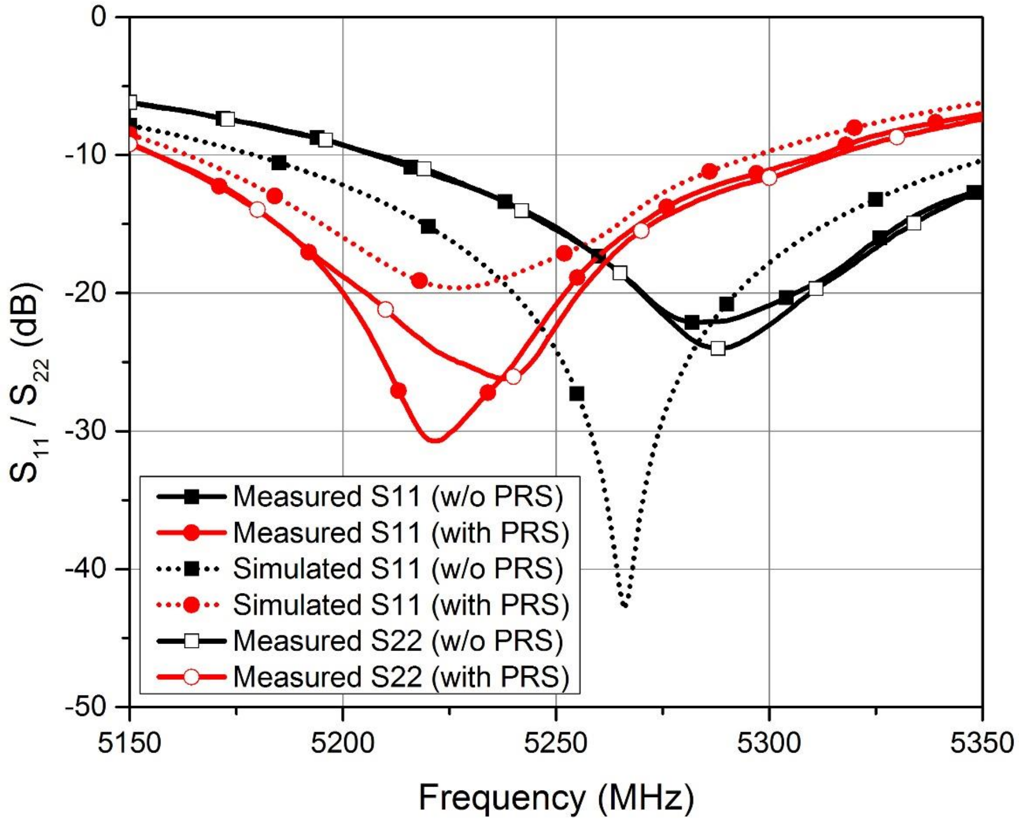
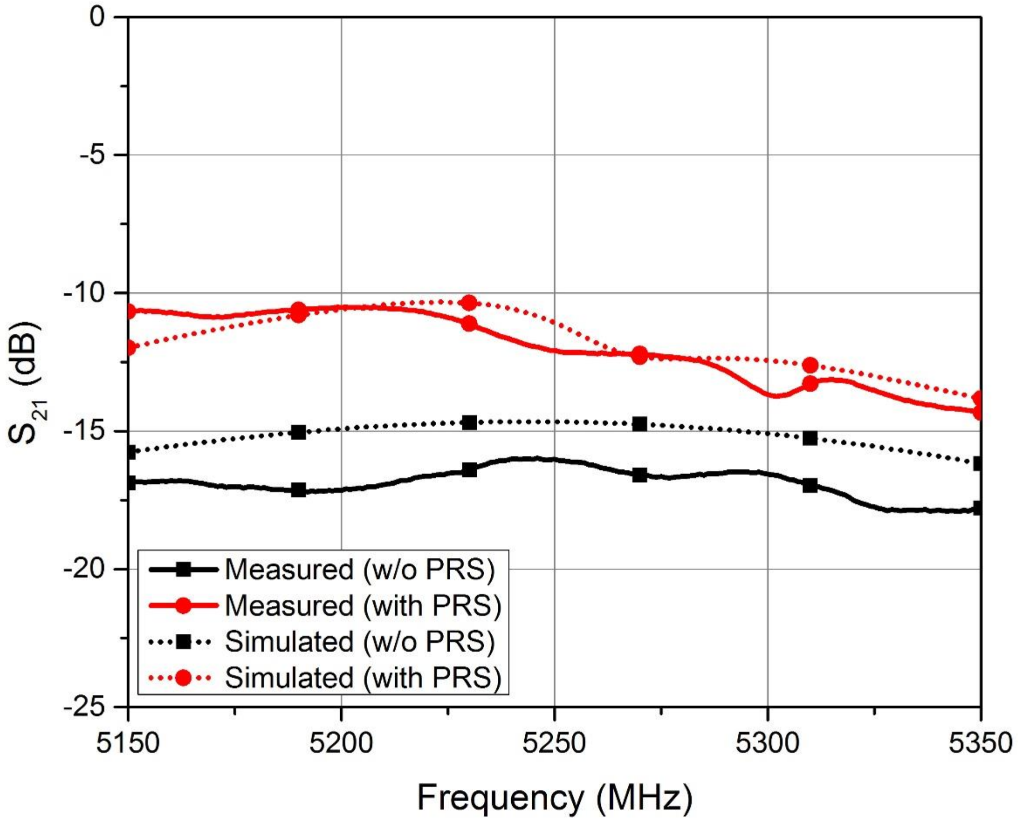
Design Examples : 2-Element MIMO Antenna

S-Parameters



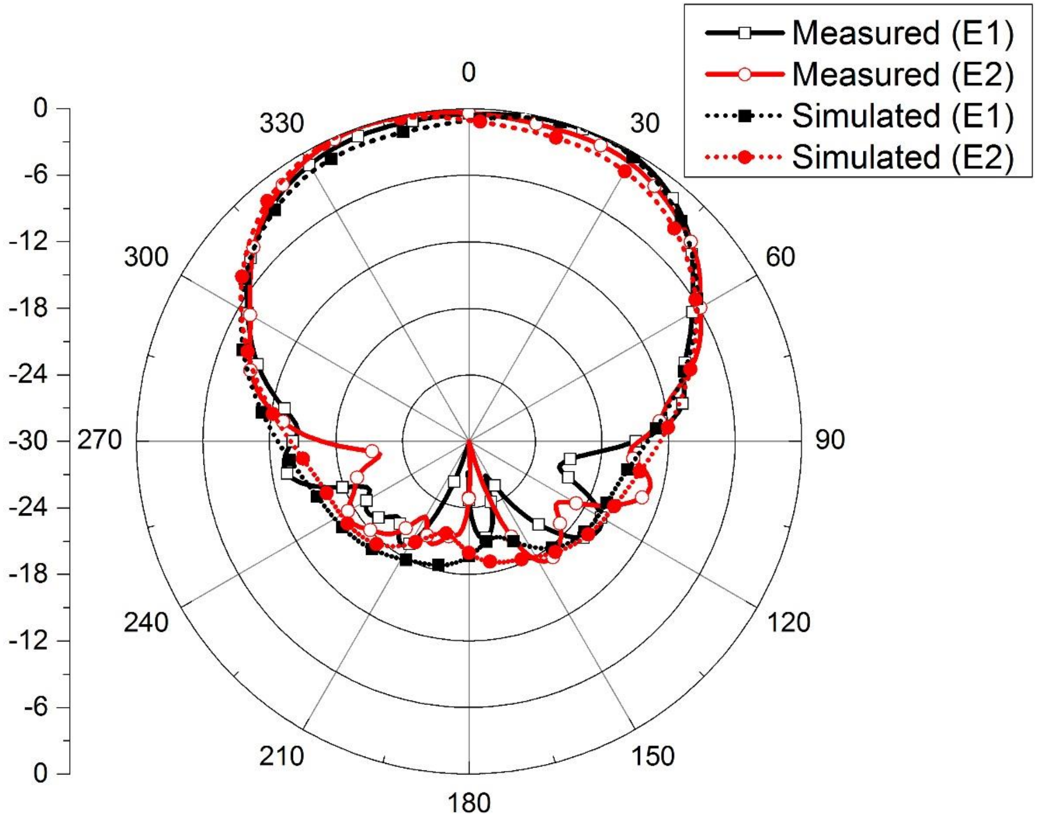
Reflection Coefficient



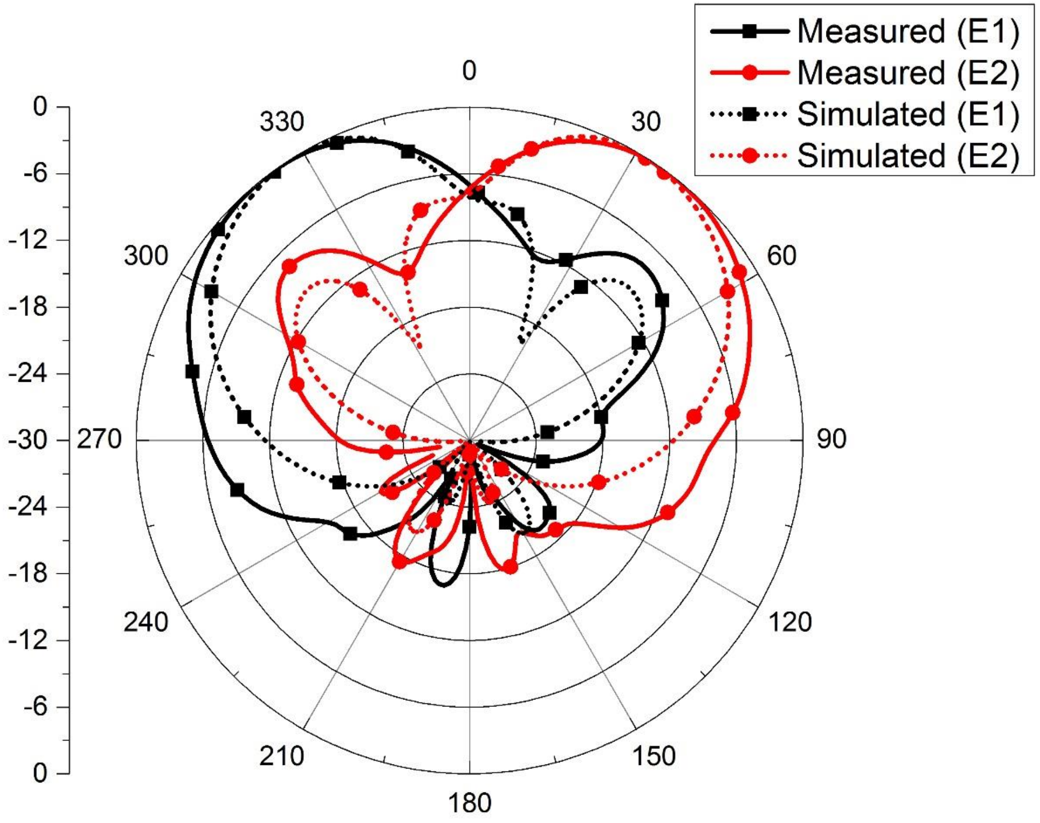
Isolation

Design Examples : 2-Element MIMO Antenna

Radiation Patterns



Without PRS (5.25 GHz)



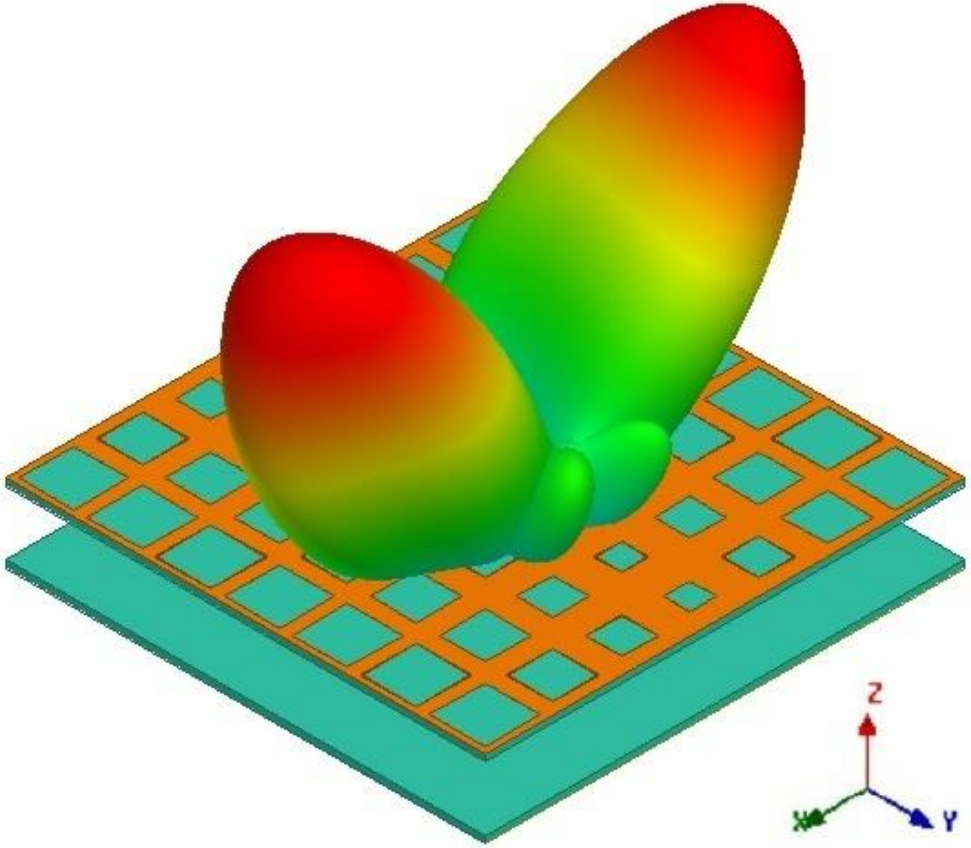
With PRS (5.25 GHz)

Design Examples : 2-Element MIMO Antenna

Radiation Patterns (contd.)

Radiation Parameters at 5.25 GHz

	Without PRS	With PRS
Directivity	7.8 dB	10 dB
Radiation Efficiency	98.5 %	91.7 %
Gain	7.73 dB	9.17 dB



3D Visualization of Radiation Patten Decorrelation

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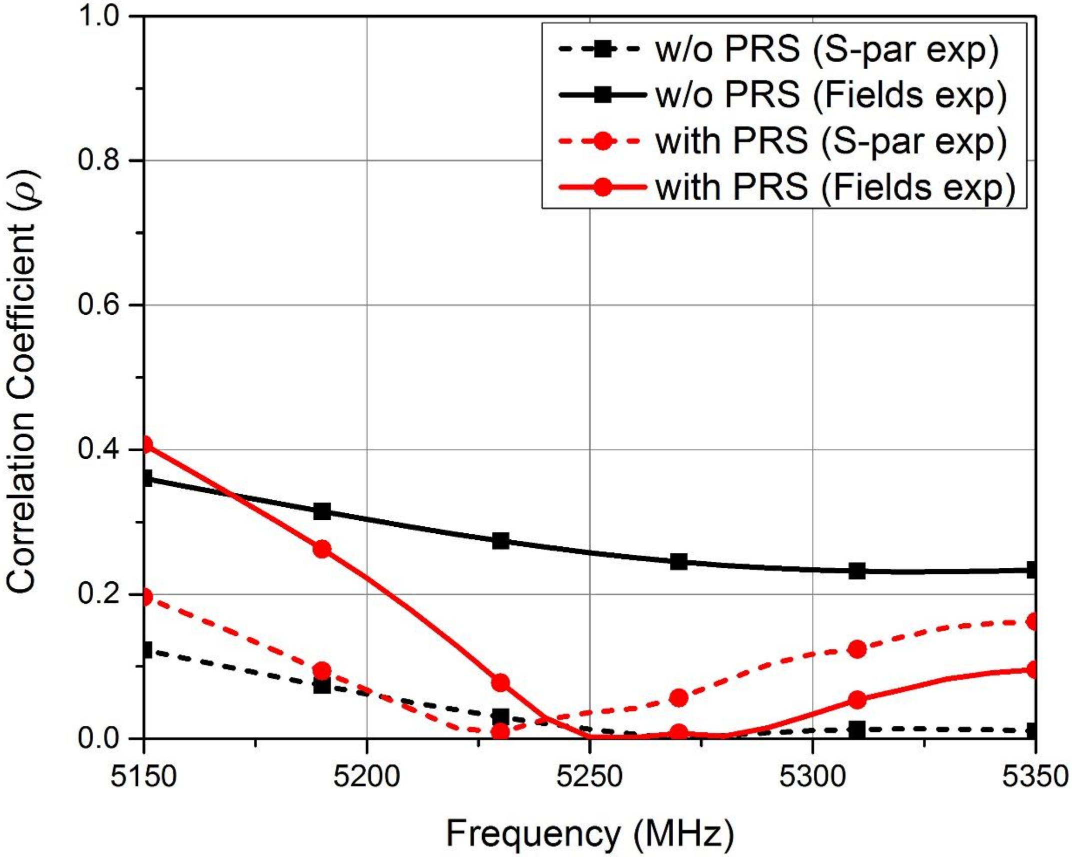
Design Examples : 2-Element MIMO Antenna

Correlation Coefficient



Correlation Coefficient at 5.25 GHz

	S-Par. Exp.	Fields Exp.
Without PRS	0.0134 ⟷	0.2575
With PRS	0.0339 ⟷	0.0022

Different

=

99.15% reduction
(although isolation↓)

*S. M. Mikki and Y. M. Antar, "On cross correlation in antenna arrays with applications to spatial diversity and mimo systems" IEEE TAP, 2015

*M. S. Sharawi, A. T. Hassan, and M. U. Khan, "Correlation coefficient calculations for mimo antenna systems: a comparative study" IJMWT, 2017

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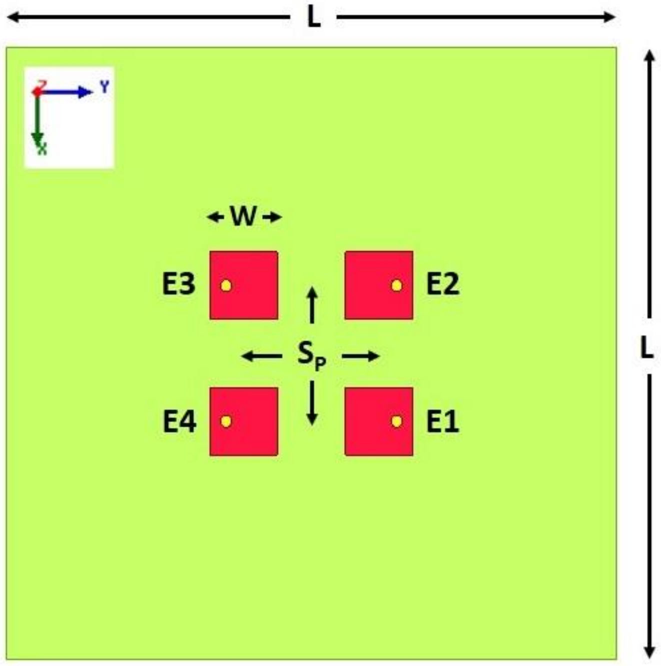
Design Examples

4-Element MIMO Antenna

- 4-Element MIMO Antenna designed for X-band
- Designed on Rogers RO4003C substrate

Parameter	Value
Width of Patch	7 mm
Length of Patch	5.84 mm
Spacing between antenna elements	7 mm (0.23λ)
Minimum Isolation	-16 dB
Total length of Board (L)	63 mm



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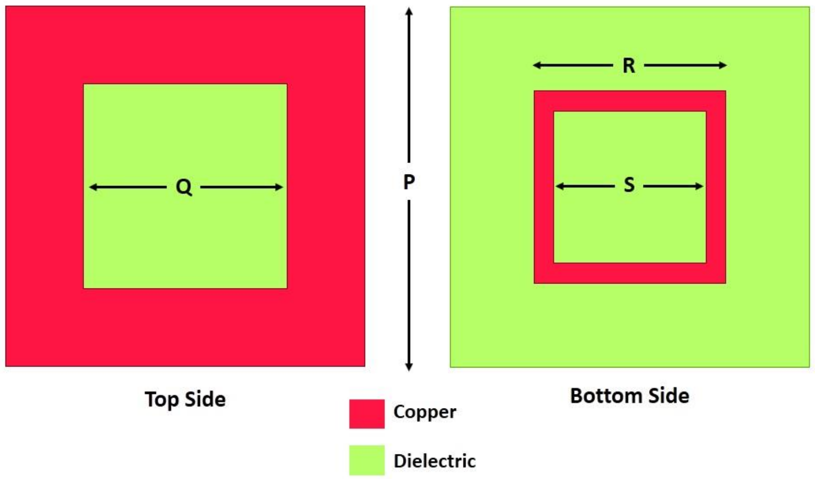
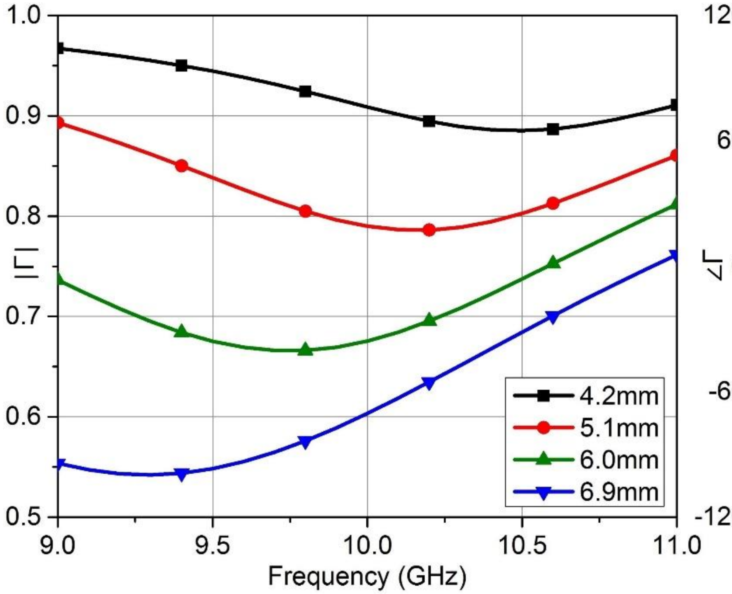
Design Examples : 4-Element MIMO Antenna

PRS Unit Cell

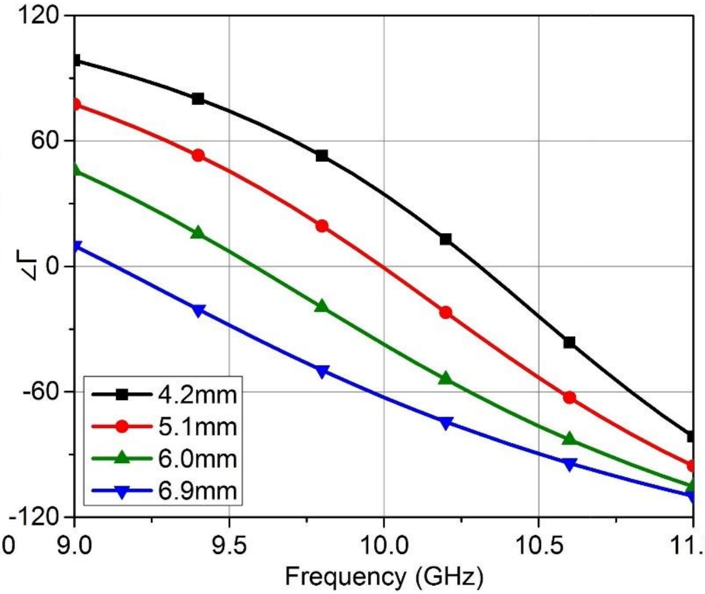

Q
P
R
S
Top Side
Bottom Side
🟥 Copper
🟩 Dielectric

- Substrate: Rogers RO4003C (ε_r=3.55, h=1.52mm)
- R =4.8mm, P = 9 mm (0.56 λ_g), Q is varied
- Simulation as a periodic structure carried out in HFSS



(a)

Reflection Magnitude



(b)

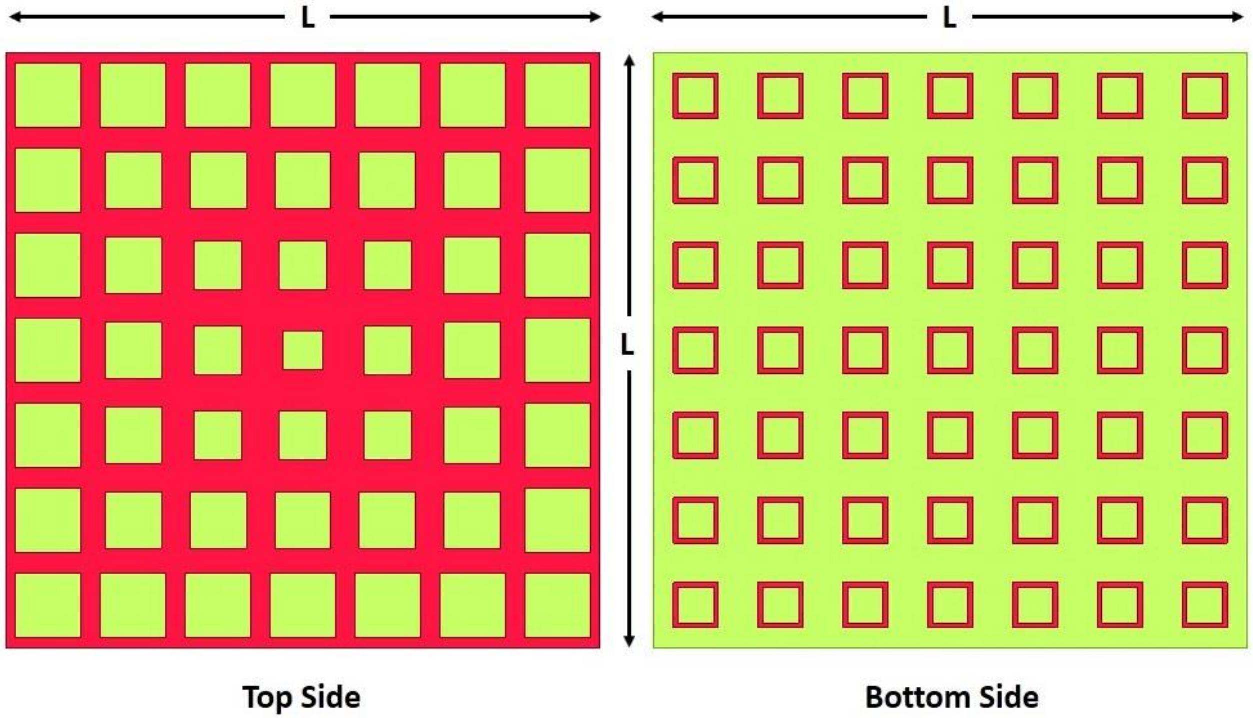
Reflection Phase

PRS Design

Values at 10 GHz

ID	Q(mm)	Magnitude	Phase (deg)
1	4.2	0.93	60.7
2	5.1	0.82	28.6
3	6.0	0.67	-10.6
4	6.9	0.56	-42.8

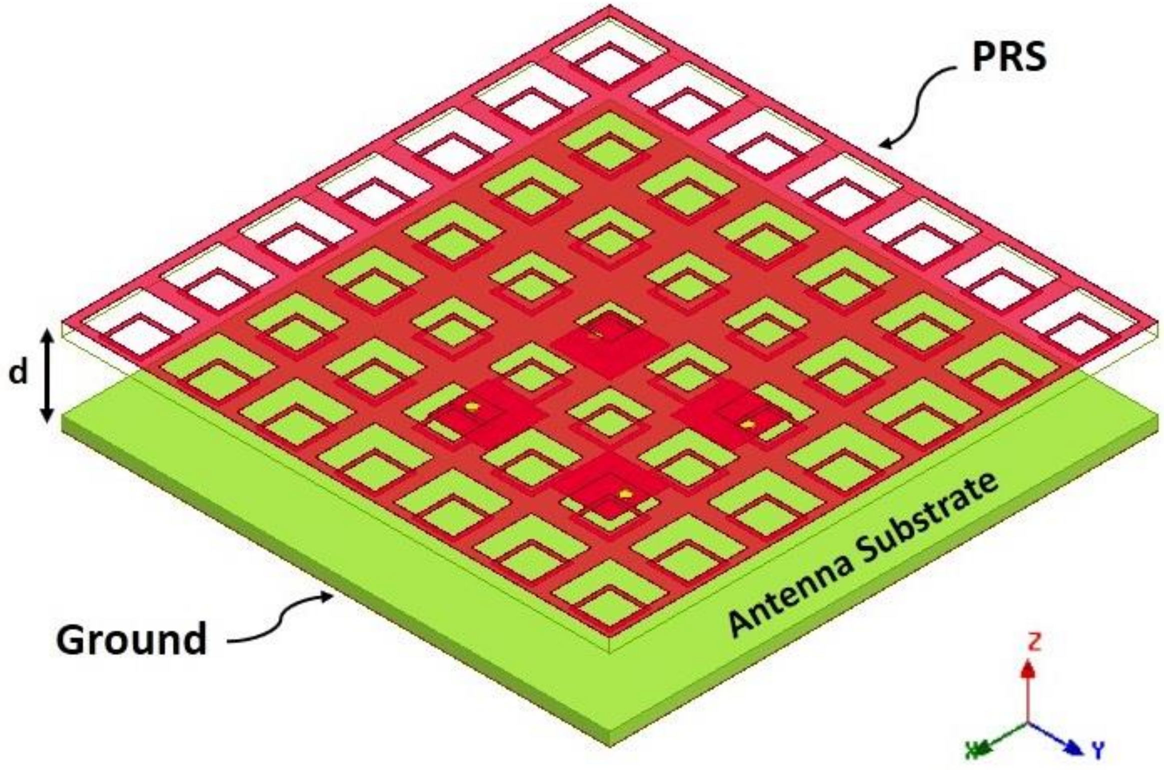
- 7 x 7 unit cells
- L = 63 mm (2.1 λ)



Design Examples : 4-Element MIMO Antenna

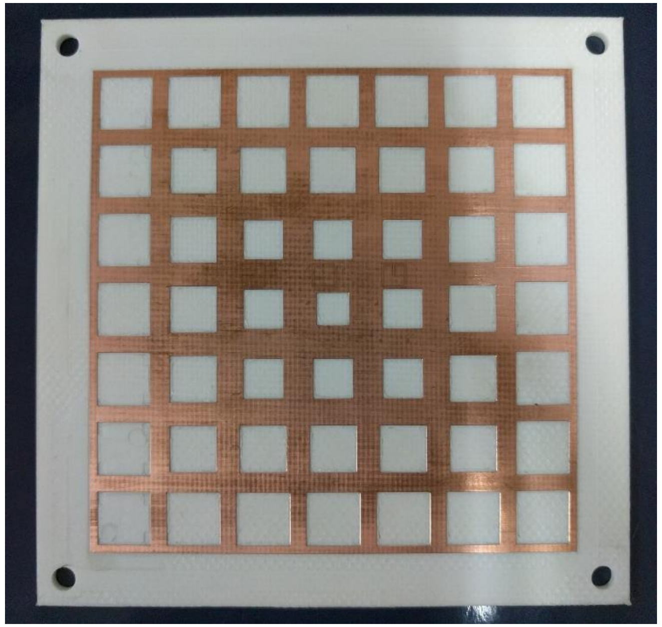
Assembled System

- d = 7.8 mm (~λ/4)

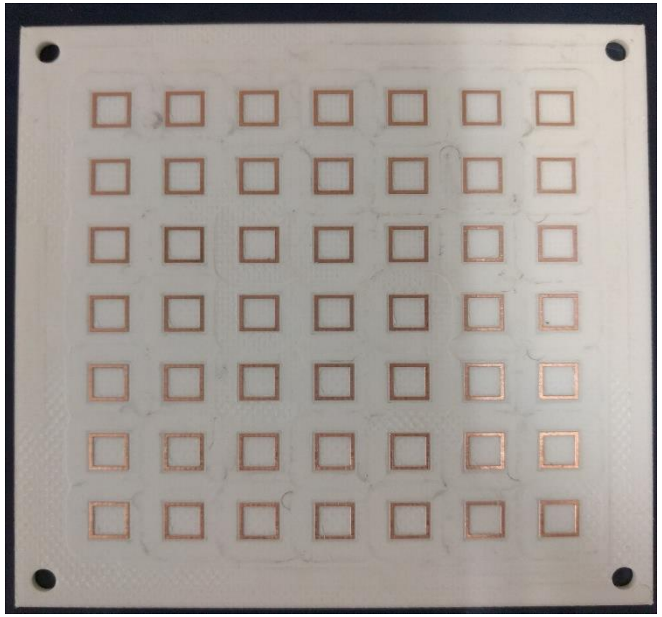

PRS
d
Ground
Antenna Substrate
Z
X
Y

Design Examples : 4-Element MIMO Antenna

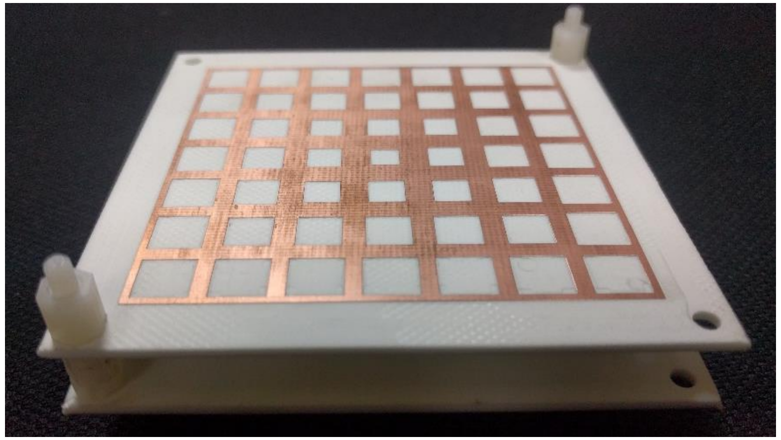
Fabricated Prototype



Top Side



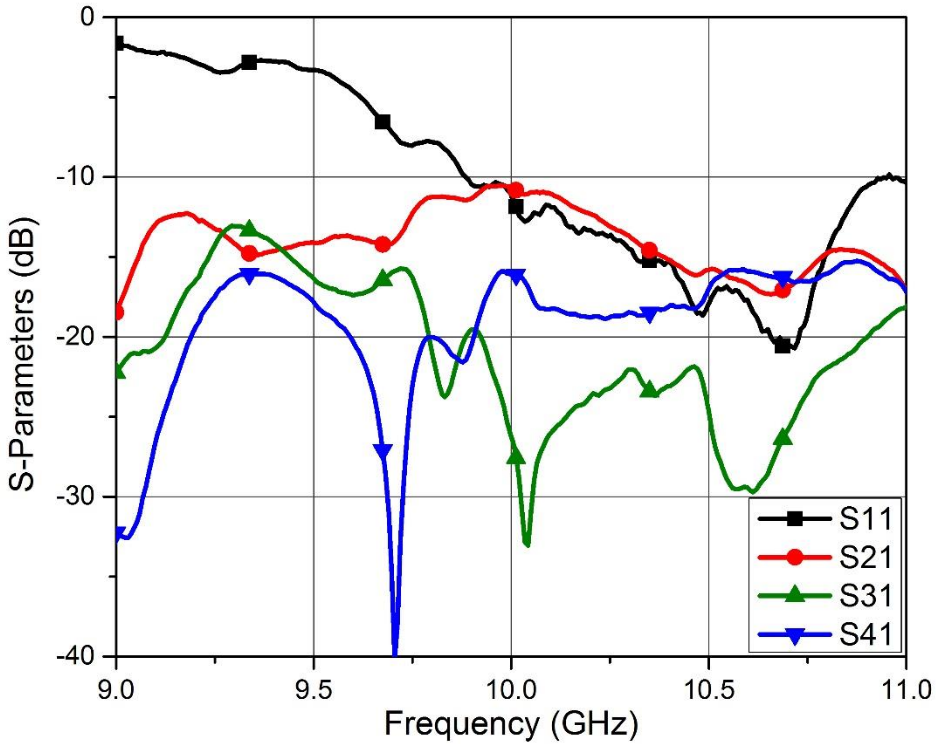
Bottom Side

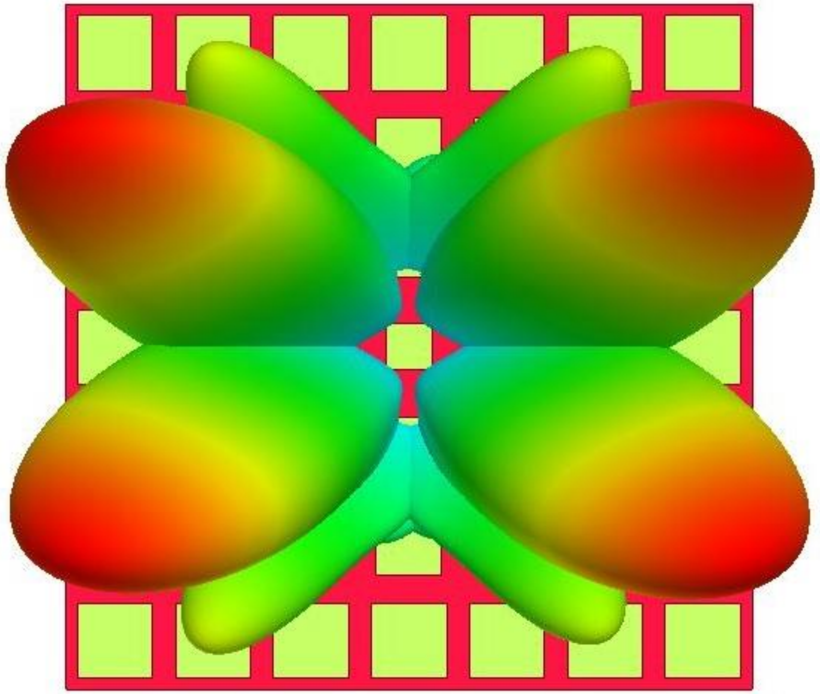


Assembled System

Design Examples : 4-Element MIMO Antenna

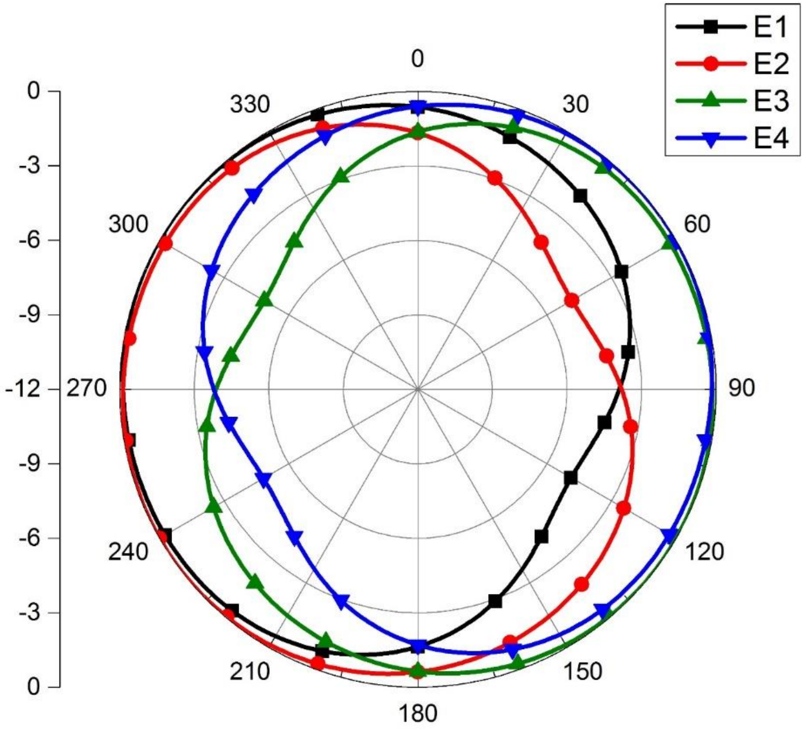
S-Parameters and 3D Patterns



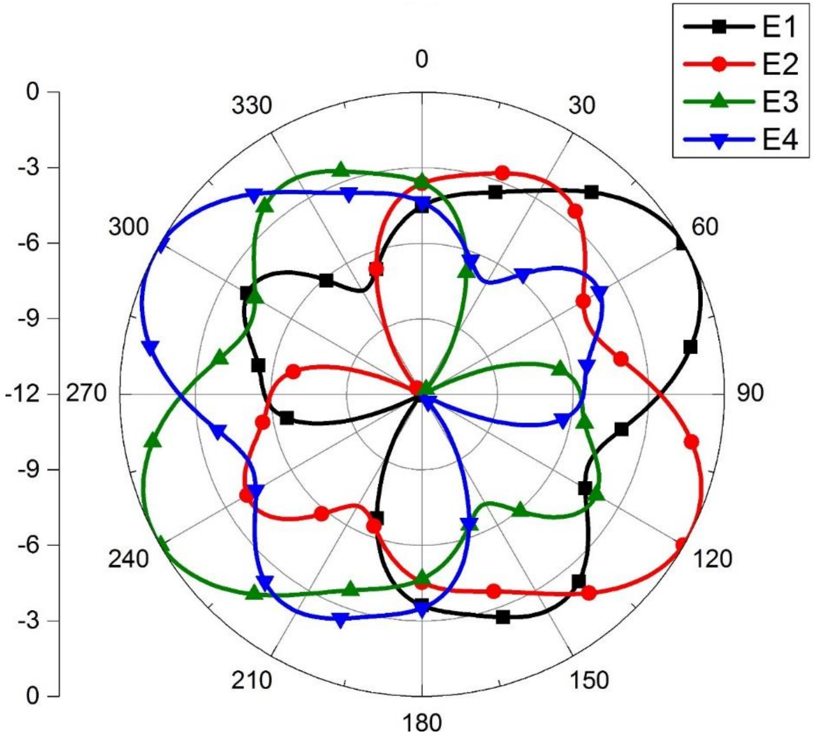


Design Examples : 4-Element MIMO Antenna

Radiation Patterns



Without PRS (10 GHz)



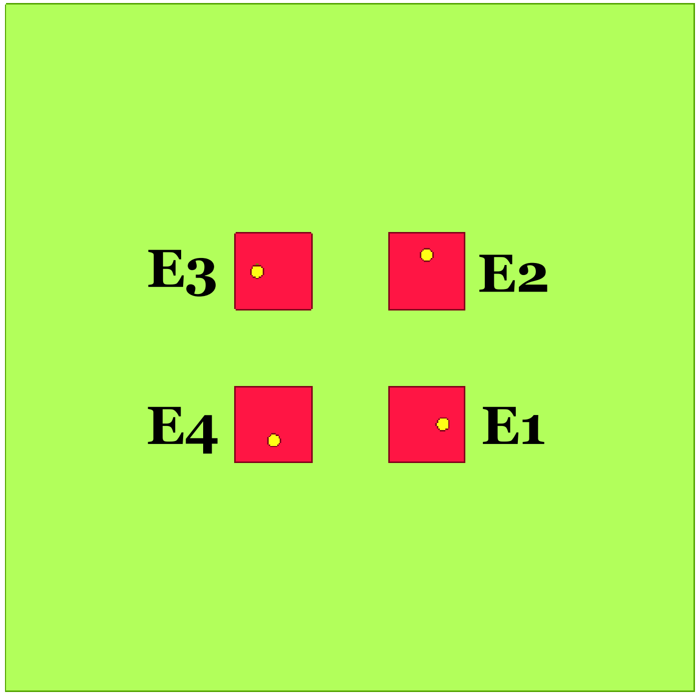
With PRS (10 GHz)

Design Examples : 4-Element MIMO Antenna

Correlation Coefficient

Correlation Coefficient Calculation based on Fields Equation at 10 GHz

	ρ_{12}	ρ_{13}	ρ_{14}
Without PRS	0.3059	0.2475	0.3045
With PRS	0.0850	0.0285	0.0982
Reduction	72.2%	88.5%	67.8%



Conclusions

Achieved

1. FSS Based Decorrelation Technique
2. General design guideline
3. Works for 2-element and 4-element MIMO Designs
4. Used easily with any radome enclosed antenna / systems

Limitations

- Valid for isotropic environment
- Cavity height is quarter wavelength
- Limited to uni-directional antennas with ground plane
- Band limited due to the use of FP Cavity

Way Forward

- Should be studied for more practical propagation environments
- Design modification for other antenna element types
- Bandwidth increase methods
- Cavity height reduction